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Decoupling China's economic growth from carbon emissions: Empirical studies from 30 Chinese provinces (2001–2015)

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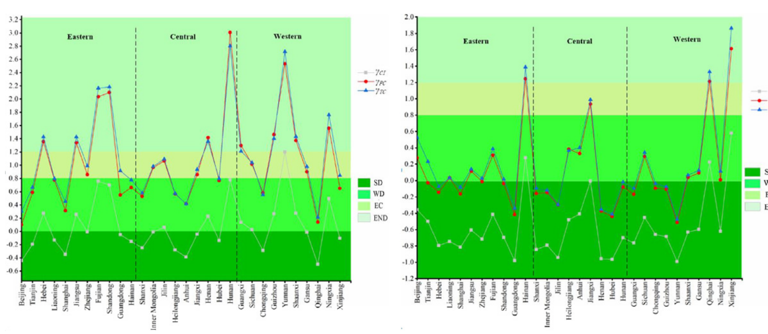
HIGHLIGHTS

- Decoupling degree of three carbon indexes in 30 Chinese provinces is analyzed.
- China has made great strides in decoupling economic growth from carbon emissions.
- Improving energy efficiency is the most effective way to control carbon emission.
- The understanding of impact factors offers references for emission mitigation.

GRAPHICAL ABSTRACT



(a) Decoupling results during the 10th *FYP* period (2001-2005)

(b) Decoupling results during the 12th *FYP* period (2011-2015)

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ABSTRACT

The world has witnessed unparalleled economic development over the past decades, but accompanied by large amount of carbon emissions, which triggered the global warming. It is critical for the global sustainable development by decoupling economic growth from carbon emissions at country level, specifically for the largest emitter, China. This study conducts a decoupling analysis from the perspective of carbon intensity (*CI*), per capita carbon emissions (*PC*) and total carbon emissions (*TC*) with reference to 30 Chinese provinces, covering the period of 2001–2015. Based on the Log Mean Divisa Index (LMDI) method, the effects of energy structure (*ES*), energy intensity (*EI*), economic output (*EO*) and population size (*P*) on *TC* at provincial level are investigated. Results show that: (1) a strong decoupling relation between *GDP* and *CI* is found in most provinces except Hainan, Qinghai and Xinjiang, while there is large room for China to decouple completely from *PC* and *TC*; (2) *EO* and *EI* are the dominated inhibiting and promoting factors respectively for carbon emission reduction; (3) *ES* effect on increasing carbon emission changes between positive and negative, while *P* has a positive but insignificant effect on the increase of carbon emissions for most provinces. The results help local governments formulate measures to coordinate regional economic development and carbon emission reduction.

Abbreviations: Abbreviation, term; IPCC, intergovernmental panel on climate change; GDP, gross domestic product; OECD, organization for economic cooperation and development; CI, carbon intensity; PC, per capita carbon emission; TC, total carbon emission; SD, strong decoupling; WD, weak decoupling; RD, recessive decoupling; SND, strong negative decoupling; WND, weak negative decoupling; END, expansive negative decoupling; EC, expansive coupling; RC, recessive coupling; LMDI, log mean divisa index; ES, energy structure; EI, energy intensity; EO, economic output; P, population; FYP, five-year plan.

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1. Introduction

It is widely appreciated that the world has undergone unparalleled economic development since the industrial revolution. However, this dramatic economic growth relies on the throughput of material and energy, producing a large amount of carbon emissions as by-products (Schandl et al., 2016; Shuai et al., 2017a; Zhang et al., 2018). According to the Intergovernmental Panel on Climate Change (IPCC, 2013), the content of carbon dioxide in the atmosphere increased progressively at a speed of 2.0 ppm per year. In 2014, global carbon emissions reached 36.14 billion tons, increased by about triple comparing to that in 1960 (World Bank, 2018). It is widely appreciated that carbon emissions have triggered global warming, which is the most serious challenge to the natural ecological system and human survival and development (Shi et al., 2017). According to the report by the United National Office for Disaster Risk Reduction (UNODRR, 2015), extreme weather linked to global warming has killed more than 600,000 people and inflicted economic losses of over 1.9 trillion dollars in the past two decades. Therefore, the interaction between the growth in economic activities and carbon emissions is highly associated with climate change, and it is urgent to decouple economic growth from carbon emissions at country level. It means to pursue a slow or even zero growth of carbon emissions whilst economic scale remains growing (Deutch, 2017; Zhang et al., 2017).

China, as the rapidly growing economy as well as the largest carbon emitter in the world, is encountering the greatest pressure to coordinate economic growth and carbon emissions. On one hand, China's economy has experienced sustained take-off and become the second largest economy in the world (Chen et al., 2017b; Zhang et al., 2019). According to the World Bank (2017), the Chinese Gross Domestic Product (*GDP*) has increased at an annual rate of 9% during 1978–2016. However, as the largest developing country, China has an urbanization rate of 58.52%, which is far from that in the developed countries (80%), and its rapid urbanization process and economic development will remain proceeding. On the other hand, the Chinese shooting up economy is driven by consuming great amount of fossil fuels, resulting in the expansion of total carbon emissions of the country from 1462 Mt in 1978 to 10291 Mt in 2014. In 2016, China emitted 27.3% of the world's total carbon emissions, which are nearly double those of the second emitter, namely, United States (BP, 2017; Dong et al., 2018b). Xu et al. (2015) warned that China's total carbon emissions would be more than 13 billion tons in 2020, and carbon emissions per unit of *GDP* would reach twice as the global average. The International Energy Agency (IEA, 2013) forecasted that by 2035, China's share of global carbon emissions would reach 33% in tandem with its rapid urbanization process and economic growth. Some argued that the goal of controlling global warming will be significantly difficult to be achieved unless the pace of emissions slows down in China (Cohen et al., 2018). Therefore, it is imperative for China to seek solutions that economic development is less dependent on the consumption of fossil fuels which generate carbon emissions intensively.

In order to coordinate economic growth and carbon emissions, the Chinese government has made ambitious plans. The government promised to reduce carbon emissions intensity by 40–45% from 2005 by 2020 in the 2009 Copenhagen conference on Climate Change. In its 12th Five-Year plan (*FYP*) (2011–2015), the Chinese National Development and Reform Commission set a target to drop energy intensity and carbon intensity by 16% and 17% respectively. In response to the Paris Accord produced in 2015, China committed that its carbon intensity would be reduced by 60–65% during 2005–2030 and its total carbon emissions would peak before 2030. To achieve these ambitious commitments, the national emissions mitigation goal must be distributed to individual provinces and cities, which are the direct executive bodies for emission mitigation (Shen et al., 2018a). However, there are many heterogeneities among regions, such as resource endowment, historical development, and industrial structure. There is no universal emissions mitigation strategy applicable to all regions. This is the case in China where individual provinces are different in multiple aspects. Therefore, the Chinese government should formulate relative emission reduction policies for different provinces (Yang et al., 2018). To do that effectively, it is essential for the government to understand the decoupling states between economic growth and carbon emissions in different provinces, so as to formulate local emission mitigation measures at minimum economic cost (Hao et al., 2016).

The decoupling theory was firstly proposed by the Organization for Economic Cooperation and Development (OECD), and defined as disconnecting the relationship between economic growth and environmental pressure (Chen et al., 2017a; OECD, 2002). The decoupling of resource use and environmental effects from economic growth has been the priority issue concerned by international institutions (Yu et al., 2017), such as the European Commission, the OECD and the International Resource Panel of the United Nations Environmental Programme (UNEP, 2011). There is also an expanding body of literature on decoupling with the focus on various sources of environmental pressure, such as energy consumption, SO_2, soot and wastewater (Csereklyei and Stern, 2015; Guevara and Domingos, 2017; Román et al., 2018; Yu et al., 2013; Yu et al., 2017). Particularly, since the consequences of global warming become pronounced, researchers globally have been seeking for solutions in order to decouple economic growth from carbon emissions. For instance, Freitas and Kaneko (2011) examined the decoupling degree between economic growth and carbon emissions in Brazil from 2004–2009 by applying the OECD decoupling indicator, and found that the absolute decoupling occurred in 2009. By using the Tapio decoupling indicator, Wang et al. (2018) compared the decoupling state of economic growth from carbon emissions in China and the United States during 2000–2014, suggesting that the decoupling performance in the United States was more stable than that in China. To illustrate the use of various decoupling indicators, Grand (2016) conducted a decoupling analysis between *GDP* and carbon emissions in Argentina from 1990–2012, and found that almost all types of decoupling states occurred during the surveyed period. Wu et al. (2018b) discussed the decoupling trends between economic growth and carbon emissions in typical developed and developing countries in 1965–2015, and pointed out that developed countries are more able to reduce carbon emissions without inhibiting economic growth. Shuai et al. (2019) investigated the decoupling status of economic growth from carbon emissions in 133 countries, suggesting that improving income level can spur the absolute decoupling.

Focusing on China, a series of decoupling investigations between economic growth and carbon emissions were carried out, which mainly fall into two streams. One research stream has been focusing on the investigation of various decoupling indicators in order to examine the decoupling status of the whole country (Luo et al., 2017; Ma and Cai, 2019; Riti et al., 2017; Tang et al., 2014; Wang et al., 2017b; Zhao et al., 2016) or several provinces (Wang et al., 2016; Yu et al., 2017; Zhang and Wang, 2013). However, decoupling analysis alone cannot evaluate the effects of environmental externalities and capture the genuine information for improvement (Diakoulaki and Mandaraka, 2007). To break through this limitation, another group of researchers have been investigating the inner mechanism of decoupling by integrating decoupling indicator with the decomposition method. For example, by integrating the decoupling index with log mean Divisia index (LMDI) model, Zhang and Da (2015) investigated the main factors affecting carbon emissions in China and explored the decoupling level between economic growth and carbon emissions. Their study suggested that energy intensity and energy consumption structure are the main drivers for decoupling. Based on Tapio decoupling index and LMDI model, Wu et al. (2018a) explored the decoupling relationship between economic growth and carbon emissions and the impact factors of the relationship in the Chinese construction industry. Wang et al. (2013b) found that energy intensity was the most significant factor for decoupling economic growth from carbon emissions in Jiangsu province, while economic

activity played an essential role in recoupling. There are still other similar studies investing the inner mechanism of decoupling from the perspective of the whole country (Yang et al., 2018; Zhang et al., 2016; Zhao et al., 2017; Zhou et al., 2017) and several provinces (Chen et al., 2018; Lu et al., 2015; Wang and Yang, 2015).

The above discussions show that many scholars have examined the decoupling states between economic growth and carbon emissions and the internal attribution of decoupling for the whole China or a few provinces. It seems that a holistic perspective of all provinces is missed. Since the goal of carbon emission reduction request for the joint efforts from all provinces, it is necessary to investigate the decoupling status for each individual province in order to formulate tailor-made emission mitigation measures for different provinces. Furthermore, as there are three typical carbon indicators for describing regional carbon emission scenarios, namely, carbon intensity (*CI*), per capita carbon emissions (*PC*) and total carbon emissions (*TC*) (Bai et al., 2016), this study will understand the decoupling status at provincial level by taking into account all the three indicators.

There are two specific objectives in this study: (1) to examine the decoupling trends of the 30 provinces in China from the perspective of *CI*, *PC* and *TC*; and (2) to find out the driving forces of *TC* for the 30 provinces. To achieve these objectives, the following questions will be addressed. How far does the Chinese economy decouple from carbon emissions at the provincial level? What are the decoupling states for each province? What is the dominate factor for the change of decoupling in each province?

The innovation and contribution of this study mainly lie in the following two aspects. Firstly, this is the first study to investigate the decoupling state between economic growth and carbon emissions among all provinces in China. This allows local governments understand comprehensively their own decoupling states, and realize the gap among the provinces. Secondly, this study provides an insight for understanding the decoupling relationship between economic growth and carbon emission through investigating not only the carbon emission indicators (carbon intensity, per capita carbon emissions and total carbon emissions) but also the emission impact factors. In this regard, local governments can formulate a reasonable target for decoupling, and adopt effective measures by addressing key factors for pursuing low-carbon economy. The new insight for decoupling analysis can also be extended to other countries internationally for analyzing carbon emissions and other environmental pressures such as SO_2, water pollution, and soot.

2. Research methodologies

2.1. Decoupling indicators

There are various methods applied in decoupling research, among which the OECD (2002) and Tapio (2005) are the two mainstreams (Ma and Cai, 2019; Wu et al., 2018a). As mentioned above, decoupling analysis was firstly introduced by OECD (2002), which refers to track the temporal changes in the relationship between environmental pressure (*EP*) and economic performance (driving force, denoted as *DF*). The OECD decoupling analysis is described as:

$$\gamma = 1 - \frac{EP^t/DF^t}{EP^0/DF^0} \tag{1}$$

where the superscripts *0* and *t* are the based year and targeted year, respectively. γ γdenotes the decoupling indicator. The value of γ can be in three situations, namely, $\gamma \le 0$, $0 < \gamma \le 1$,and $\gamma > 1$. The situation of $\gamma < 0$ indicates that there is no decoupling. $0 < \gamma \le 1$ indicates the occurrence of decoupling during a certain period. γ closer to 1 implies a greater decoupling degree. Although the OECD decoupling model (1) is easy for application, its drawback is also obvious. First, it is highly sensitive to the choice of benchmark years, leading to the poor stability of the calculated results (Zhao et al., 2016). Second, the model can only roughly uncover the two states: decoupling and no decoupling, and unable to interpret minor changes (Zhao et al., 2017). Third, the measuring precision is not very accurate for the corresponding value of γ, which may be the same in the situation that *EP* is not decreasing when the *DF* is in expansion and that *EP* is decreasing but with *DF* stagnating or falling (Grand, 2016).

The another widely employed decoupling indicator putted forward by Tapio (2005) comes to solve those weaknesses (Wu et al., 2018a). Instead of measuring the absolute value of variables, Tapio decoupling introduced the concept of elasticity to measure the sensitivity on incremental values. Tapio decoupling model is therefore chosen in this study to examine the decoupling of economic growth (*GDP*) from carbon emissions (indicated by carbon intensity (*CI*), per capita carbon emissions (*PC*) and total carbon emissions (*TC*)). Taking *TC* as an example, the decoupling elasticity γ_{TC} is expressed as follows:

$$\gamma_{TC} = \frac{\Delta TC/TC^0}{\Delta GDP/GDP^0} = \frac{\left(TC^t - TC^0\right)/TC^0}{\left(GDP^t - GDP^0\right)/GDP^0} \tag{2}$$

In Eq. (2), ΔTC and ΔGDP denotes the change of total carbon emissions and economic growth between a base year *0* to a target year *t* respectively. In order to over-interpret slight changes as significant, a $\pm$ 20% variation of elasticity values around 1.0 is given for finely distinguishing the decoupling states. Decoupling states corresponding to γ_{TC} can be presented in Figure 1, which are classified into three categories and eight sub-categories (Tapio, 2005).

i. Decoupling state generally means the situation when the growth of *TC* is lower than *GDP*. It indicates that the dependence of economic growth on *TC* is weakening. Furthermore, it can be divided into three states, namely, strong decoupling (*SD*), weak decoupling (*WD*) and recessive decoupling (*RD*). *SD* is the ultimate goal of pursuing low carbon economy, while *RD* is unsatisfactory because of the negative economic growth.
ii. The coupling state occurs in the situation that *TC* and *GDP* present almost consistent growth rate. It indicates that the dependence between economic growth and *TC* is reinforced. There are two coupling states, namely, expansive coupling (*EC*) and recessive coupling (*RC*).
iii. Negative decoupling state is the situation when *TC* grows faster than *GDP*. It can be divided into three states, namely, strong negative decoupling (*SND*), weak negative decoupling (*WND*) and expansive negative decoupling (*END*). These three states are unsatisfactory due to the high dependence of economic growth on *TC*.

2.2. Decomposition model for carbon emissions

Decomposition model is widely used to investigate the driving forces on *TC*. There are mainly two types of decomposition techniques, namely, structural decomposition analysis (SDA) and index decomposition analysis (IDA) (Zhao et al., 2016). The IDA has more obvious advantages compared with the SDA. First, the SDA method requires a complete input-output table of a country or region, which is usually produced every five years. Thus, the data used are not most updated. However, the IDA method is based on time-series data and the data are most updated (Yang et al., 2018). Second, the application scope of the IDA method is wider and mainly focused on research objects with less driving factors (Xu and Ang, 2013). There are various IDA methods, among which the log mean Divisia index (LMDI) is the preferred model because of its better adaptability, ease for use, and good decomposition results without any unexplained residuals term (Ang, 2004). Furthermore, there are two forms of LMDI, namely additive decomposition and multiplicative decomposition. The additive decomposition is easier to use and interpret (Zhao et al., 2016). Therefore, this study adopts the additive LMDI method.

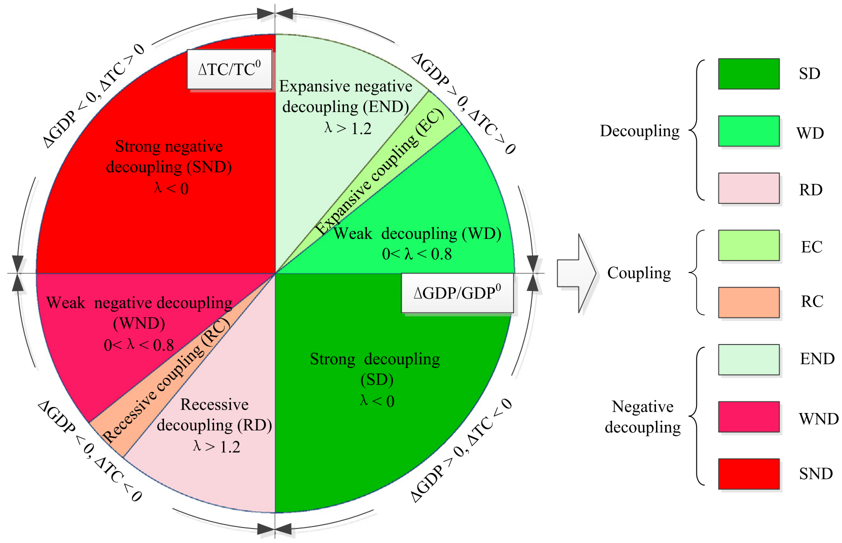


Fig. 1. Decoupling judgments of the Tapio decoupling indicator.

The LMDI can be expressed as an extended Kaya identity (Kaya, 1990), which decomposes *TC* into four types of factors, including energy structure (*ES*), energy intensity (*EI*), economic output (*EO*) and population size (*P*), described as:

$$\mathrm{TC} = \frac{\mathrm{TC}}{\mathrm{E}} \times \frac{\mathrm{E}}{\mathrm{GDP}} \times \frac{\mathrm{GDP}}{\mathrm{P}} \times \mathrm{P} = \mathrm{ES} \times \mathrm{EI} \times \mathrm{EO} \times \mathrm{P} \tag{3}$$

where *E* is the total energy consumption.

- ➢ $ES = \frac{TC}{E}$ denotes the ratio of total carbon emissions to total energy consumption, which can reflect the energy structure. Since China is predominantly dependent on coal, which is the most carbon-intensive fuel, the factor *ES* is commonly measured by the change of the proportion of coal (Zhou et al., 2017).
- ➢ $EI = \frac{E}{GDP}$ represents the ratio of energy consumption to *GDP*, which indicates the energy efficiency (Zhang and Da, 2015).
- ➢ $EO = \frac{GDP}{P}$ denotes per capita *GDP*. As economic growth is driven by consuming energy, it has a positive effect on the increase of carbon emissions (Yin et al., 2015).
- ➢ *P* reflects the total population in the concerned area, which is directly linked to the demand for energy.

According to the LMDI method, the change of *TC*, denoted as Δ*TC*, between a base year *0* and a target year *t* can be decomposed into four types of effects, including ES_{effect}, EI_{effect}, EO_{effect} and P_{effect}, shown as follows (Ang, 2004):

$$\Delta\mathrm{TC} = \mathrm{TC}^t - \mathrm{TC}^0 = \mathrm{ES}_{\mathrm{effect}} + \mathrm{EI}_{\mathrm{effect}} + \mathrm{EO}_{\mathrm{effect}} + \mathrm{P}_{\mathrm{effect}} \tag{4}$$

The calculation for these effects is according to the following formulas (Ang, 2004):

$$\mathrm{ES}_{\mathrm{effect}} = \frac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0} \times \ln\left(\frac{\mathrm{ES}^t}{\mathrm{ES}^0}\right) \tag{5}$$

$$\mathrm{EI}_{\mathrm{effect}} = \frac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0} \times \ln\left(\frac{\mathrm{EI}^t}{\mathrm{EI}^0}\right) \tag{6}$$

$$\mathrm{EO}_{\mathrm{effect}} = \frac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0} \times \ln\left(\frac{\mathrm{EO}^t}{\mathrm{EO}^0}\right) \tag{7}$$

$$\mathrm{P}_{\mathrm{effect}} = \frac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0} \times \ln\left(\frac{\mathrm{P}^t}{\mathrm{P}^0}\right) \tag{8}$$

where

$$\frac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0} = \begin{cases} \dfrac{\left(\mathrm{TC}^t - \mathrm{TC}^0\right)}{\ln \mathrm{TC}^t - \ln \mathrm{TC}^0}, \mathrm{TC}^t\mathrm{TC}^0 \neq 0 \\ \mathrm{TC}^t, \mathrm{TC}^t = \mathrm{TC}^0 \\ 0, \mathrm{TC}^t\mathrm{TC}^0 = 0 \end{cases} \tag{9}$$

A positive value of these effects indicates a net increase in *TC*, whereas a negative value reflects a net reduction in *TC*.

2.3. Data collection

In applying the models (1)–(9), data are collected from 30 provinces in China over the period of 2001–2015, except for those where the needed data are unavailable. Carbon emissions based on the consumption of fossil fuels in a concerned province are calculated by using the method proposed in the Intergovernmental Panel on Climate Change guidelines (IPCC, 2006). To obtain accurate results, 16 fossil fuels are taken into account, including raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, other gas, other petroleum products, liquefied petroleum gas, refinery gas and natural gas. Consumption data and related emission coefficients of these fossil fuels are collected from the China Energy Statistical Yearbooks (2000–2016) and IPCC (2006). To ensure comparability, fossil fuels are converted into standard coal equivalent when calculating the total energy consumption (*E*), and the standard coal coefficients for these fossil fuels are also from China Energy Statistical Yearbooks. Data about *GDP* and total population size (*P*) for the 30 provinces are derived from China Statistical Yearbooks. To accommodate the price inflation, *GDP* is normalized at 2001 constant price by using the *GDP* indices from China Statistical Yearbooks.

In line with the Chinese Five-year plan (*FYP*), this paper divides the study period (2001–2015) into three periods, namely, 2001–2005 (10^{th} *FYP* period), 2006–2010 (11^{th} *FYP* period), and 2011–2015 (12^{th} *FYP* period). The performances of *CI*, *PC*, *TC* and *GDP* for all the 30 provinces in these three *FYP* periods are presented graphically by using scatter box plot method, as shown in Fig. 2. Scatter box plot is a widely used method for data description (Dong et al., 2017; Dong et al., 2018a).

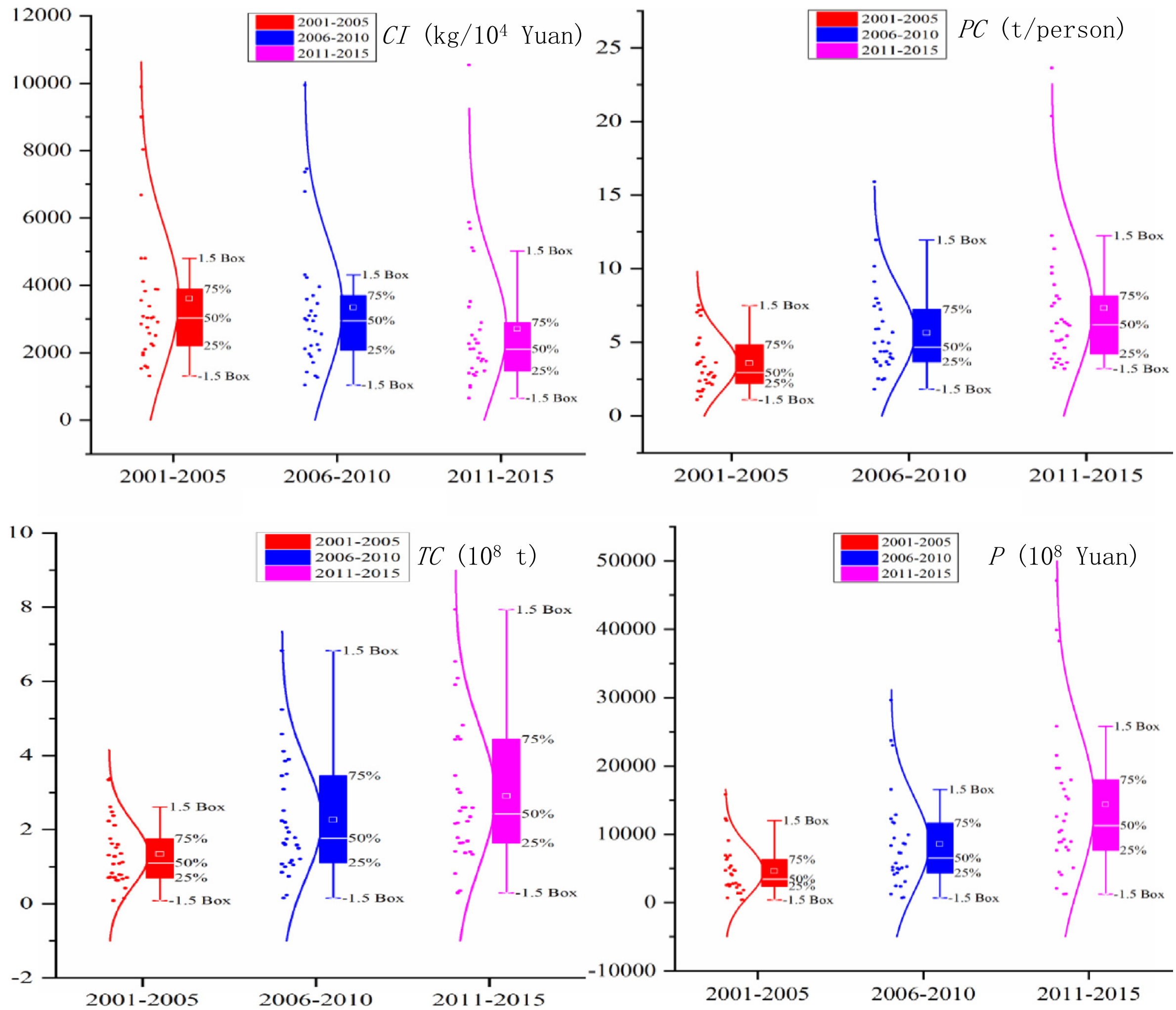


Fig. 2. Scatter box plot for the annual average of *CI*, *PC*, *TC*, *GDP* for the 30 provinces Note: The box in the figure include four values, namely, the average value between the 30 provinces (shown by the small white square), the median value (shown by the white bar), the 75th percentile (shown by top edge), and the 25th percentile (shown by bottom edge).

3. Results and discussions

3.1. Analysis on the decoupling between economic growth and carbon emissions

As mentioned in the introduction section, there are three decoupling perspectives, namely, between *GDP* and *CI*, *GDP* and *PC*, and *GDP* and *TC*. Based on the formula (2) and the decoupling judgments shown in Fig. 1, the decoupling statuses of the 30 provinces during three time periods (10th *FYP*, 11th *FYP*, and 12th *FYP*) are obtained, as shown in Fig. 3, 4 and 5 respectively.

3.1.1. Decoupling relation between GDP and CI

It can be observed from Fig. 3(a) that, during the 10th *FYP* period, there were 17 provinces who displayed the most ideal *SD* state, namely, *CI* decreased as the *GDP* growth. *WD* was found in 12 provinces, where *CI* increased with less growth amplitude than *GDP*. Meanwhile, it is remarkable that Yunnan province presented *END* state, a bad status with decoupling elasticity greater than 1.2. This is mainly due to the fact that Yunnan positioned economic development as the top priority, and there was a low efficiency in energy consumption during 2001–2005 (Xu et al., 2017). According to the report of the State Ethnic

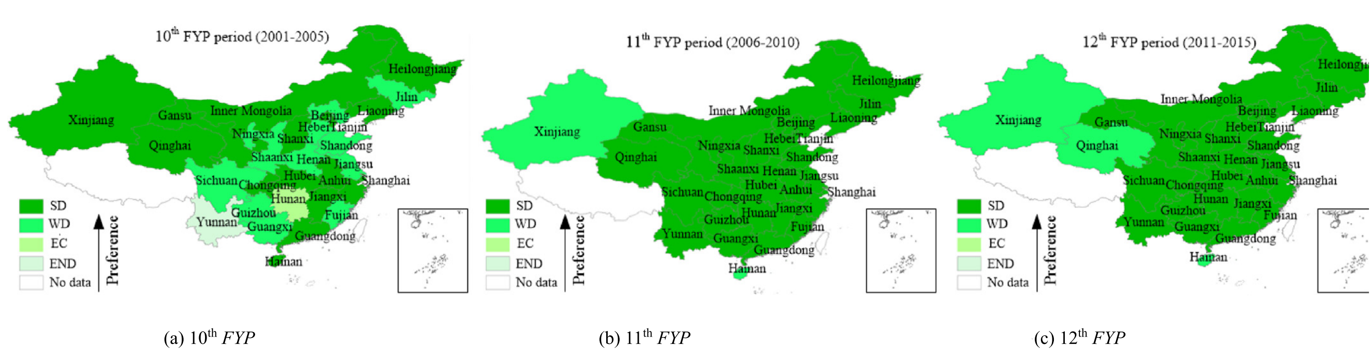
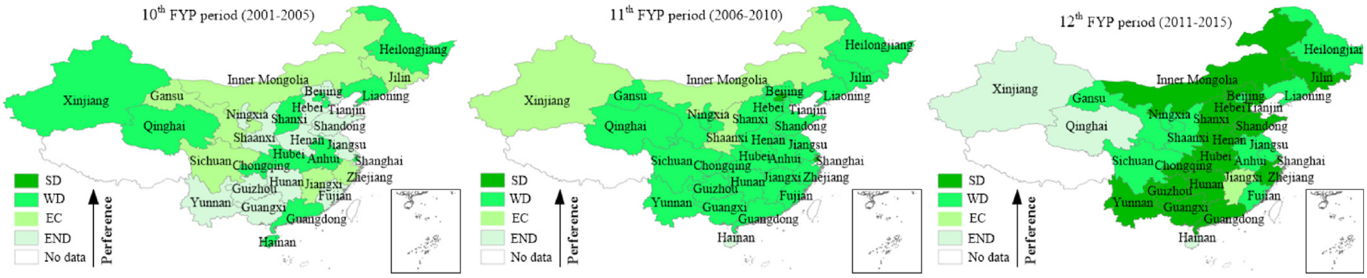


Fig. 3. Decoupling statuses for the 30 Chinese provinces during 2001–2015 from the perspective of the relation between *GDP* and *CI*.



(a) 10th *FYP* (b) 11th *FYP* (c) 12th *FYP*

Fig. 4. Decoupling statuses for the 30 Chinese provinces during 2001-2015 from the perspective of the relation between *GDP* and *PC*.

Affairs Commission of the People's Republic of China (SEAC, 2006), in the 10th *FYP* period, Yunnan's *GDP* increased rapidly with an annual average growth rate of 8.9%. However, this expanded economy was overdependent on resources and characterized by low production quality and low energy efficiency, leading to the fact that the growth rate of *CI* is much higher than that of *GDP*.

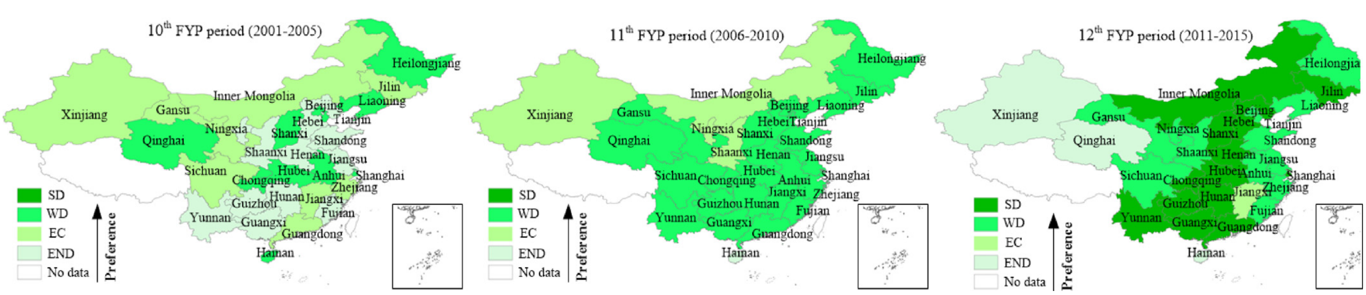
During the 11th *FYP* period, the relationship between *GDP* and *CI* present a *SD* state in the majority of provinces except for Hainan and Xinjiang (shown as Fig. 3(b)), implying that the national *CI* and energy efficiency has made a great stride in the whole country. This result is echoed with Xu et al. (2016a), suggesting that the main feature of China in the 11th *FYP* period is high energy efficiency and high economic output. It is worthy to note that although encountered with the economic crisis in 2008, China's economy still grew and *CI* declined due to the central government invested 4 trillion Yuan to stimulate the infrastructure, ecological environment construction projects, and culture education industry (Shuai et al., 2019). In addition, the government has also implemented a series of emission reduction measures during this period. For example, "the Outline of the 11th *FYP* period for National Economic and Social Development" set a target of reducing energy use per unit of *GDP* by 20% from 2005 to 2010. Energy conservation laws were enacted, and incentives for advanced energy-saving technologies were implemented. The Ministry of Commerce of the People's Republic of China formulated an implementation plan of an assessment system for energy consumption per unit *GDP* to improve the energy policy and management. And an increasing number of "high energy consumption, heavy pollution and low efficiency" enterprises were shut down. These measures are considered as effective governmental interventions for promoting low carbon economy, and can be recommended for countries internationally.

Fig. 3(c) shows that only two decoupling states occurred over the period of the 12th *FYP*, namely, *SD* (90%) and *WD* (10%).This phenomenon is similar to that for the period of 11th *FYP*. However, different from the 11th *FYP* period, in which rapid economic development was gained, the 12th *FYP* emphasized on production quality rather than just speed (Zhou and Liu, 2016). The goal of 17% reduction of *CI* has been proposed in the implementation plan of "12th *FYP* to control greenhouse gas emission". In line with this, additional policies have been issued to accelerate the adjustment of industrial structure and optimization of energy efficiency. As a result, the tertiary industry which is characterized with less carbon-intensive has dominated the national economic structure since 2013 (National Bureau of Statistics of China (NBSC), 2015b). This contributes to the improvement of energy efficiency during this period. It is worthy to note that only Hainan, Qinghai and Xinjiang provinces displayed a *WD* state, indicating energy inefficient. This is echoed in the study by Wang et al. (2013a), suggesting that these three provinces were energy inefficient, and they should pay greater attention to seriously catch up with the high-efficiency benchmark.

3.1.2. Decoupling relation between GDP and PC

The decoupling relation between *GDP* and *PC* for the three surveyed periods are illustrated in Fig. 4. Fig. 4(a) shows the decoupling state during the period of the 10th *FYP*. It can be seen that there were 13 provinces in *WD* state, meaning that *GDP* increased faster than *PC*. They are Beijing, Tianjin, Liaoning, Shanghai, Guangdong, Hainan, Shanxi, Heilongjiang, Anhui, Hubei, Chongqing, Qinghai, and Xinjiang. Only 6 provinces displayed an *EC* state with decoupling elasticity between 0.8 and 1.2, including Zhejiang, Inner Mongolia, Jilin, Jiangxi, Sichuan and Gansu. Other 11 provinces experienced an *END* state, meaning that the growth rate of *PC* surpassed that of *GDP* in these regions. Overall, the value of *PC* at national level appeared an obvious increase in the period of 10th *FYP*. This can be further evidenced by the data in the World Bank (2006), suggesting that *PC* at national level in China increased from 2.742 t/person in 2001 to 4.523 t/person in 2005, with an annual average growth rate of 13.3%.

In referring to the 11th *FYP* period, decoupling statuses were very different, as shown in Fig. 4(b). The majority of the provinces (80%) were in *WD* state, and Beijing and Shanghai were even in the state of *SD*, which implied that these two regions realized economic growth accompanied the decrease of *PC*. However, *PC* in Beijing and Shanghai surpassed that of London, Singapore, and Tokyo and other international cities (Tanpaifang, 2012). Therefore, these two municipal cities should continue to adopt effective policies for reducing *PC*. Notably, among all the provinces, only Hainan province was in the state of *END*. This conforms with the study by Huang and Meng (2013), suggesting that *PC*



(a) 10th *FYP* (b) 11th *FYP* (c) 12th *FYP*

Fig. 5. Decoupling statuses for the 30 Chinese provinces during 2001-2015 from the perspective of the relation between *GDP* and *TC*.

in Hainan province increased rapidly during the surveyed period of 2005–2010.

According to Fig. 4(c), decoupling states of the 30 provinces during the 12th *FYP* period had a significant improvement in comparing to that in the periods of 10th and 11th *FYPs*. *SD* and *WD* were the two major decoupling states during the 12th *FYP* period, in which 16 provinces were in *SD* state and 10 provinces were in *WD* state. However, this does not mean that the national *PC* has been reduced. According to the statistics of the international organization named *Global Carbon Project* (GCP, 2016), the national *PC* in China has increased to 7.5 in 2015, exceeding that in the EU, measured with the *PC* value of 7, and much higher than the global average, with the *PC* value of 4.9. It is further noted that the decoupling elasticities in Xinjiang and Qinghai were much larger than that of the other provinces. This was due to the fact that the population size of these two provinces had no obvious growth, while their *TC* grew very fast, which were driven by the Western Development Strategy (Huang and Meng, 2013; Wang et al., 2017a).

3.1.3. Decoupling relation between GDP and TC

Fig. 5 displays the decoupling relation between *GDP* and *TC* for the three surveyed periods. Fig. 5(a) demonstrates the decoupling state over the period of the 10th *FYP*. Three decoupling statuses appeared in this period, namely, *WD*, *EC* and *END*. Both *WD* and *END* states occurred in 11 provinces, while *EC* state appeared in the rest of 8 provinces. The appearance of all the states *WD*, *EC*, and *END* suggested that China's *TC* have witnessed a rapid uptrend in accompany with *GDP* growth during this period. In fact, China joined the WTO in this period, leading to the emergence of a large number of energy-intensive infrastructure projects and industrial parks (Zhou et al., 2016). Undoubtedly, this expanded production scale contributed to the boom of economy, but the increase of *TC* as well. Zhao et al. (2017) further proposed that, the growth rate of *TC* surpassed that of *GDP* in the whole China during this surveyed period.

During the 11th *FYP* period (2005–2010), the relation between *GDP* and *TC* turned to WD-oriented, as shown in Fig. 5(b). There were 25 provinces in *WD* state, 4 provinces with *EC* state, and only Hainan province was in *END* state. This evidences that the policies on energy saving and emission reduction in the 11th *FYP* period have brought good effects. The research by Zhao et al. (2017) and Ren et al. (2014) echoed this view and pointed out that carbon emission reduction in China has been mainly policy driven. In terms of Hainan's *END* state, Xu et al. (2016b) explained that the proportion of industrial output in this province is still increasing rapidly, thus it is very difficult to reduce *TC*.

Fig. 5(c) shows the decoupling states between *GDP* and *TC* in the 12th *FYP* period. It appears that the decoupling status in this period is better than that in the 10th and 11th *FYP* periods. The state of *SD* came ture in 13 provinces, including Hebei, Shanghai, Guangdong, Shanxi, Inner Mongolia, Jilin, Henan, Hubei, Hunan, Guangxi, Chongqing, Guizhou, and Yunnan. The result is not surprising since the effective policies for low-carbon economy were continuous during this period. Taken Shanxi as an example, the province stressed the adjustment of industrial structure, and launched a set of programs for reducing coal consumption to obtain sustainable economic growth (Wang and Zhao, 2014). The rest provinces except Jiangxi, Hainan, Qinghai and Xinjiang were in the state of *WD*, indicating that more attention should be focused on reducing *TC* in these provinces, particularly for Jiangxi, Hainan, Qinghai and Xinjiang. It can be concluded that the decoupling states between *GDP* and *TC* in China witnessed a clear tendency toward *WD* to *SD* in the period of 12th *FYP*, which is consistent with the findings of Zhang and Da (2015) and Zhao et al. (2017). Nevertheless, there is still a big room for China to engage in emission mitigation program, so as to complete the emission-peak commitment ahead of schedule.

3.1.4. Overall decoupling results

After analyzing the decoupling results from three perspectives, namely, γ_{CI}, γ_{PC} and γ_{TC}, this section presented these results from the period of the 10th *FYP*, the 11th *FYP*, and the 12th *FYP*. The details can be shown in Figs. 6, 7 and 8 respectively.

The results in Figs. 6–8 reveal several interesting phenomena:

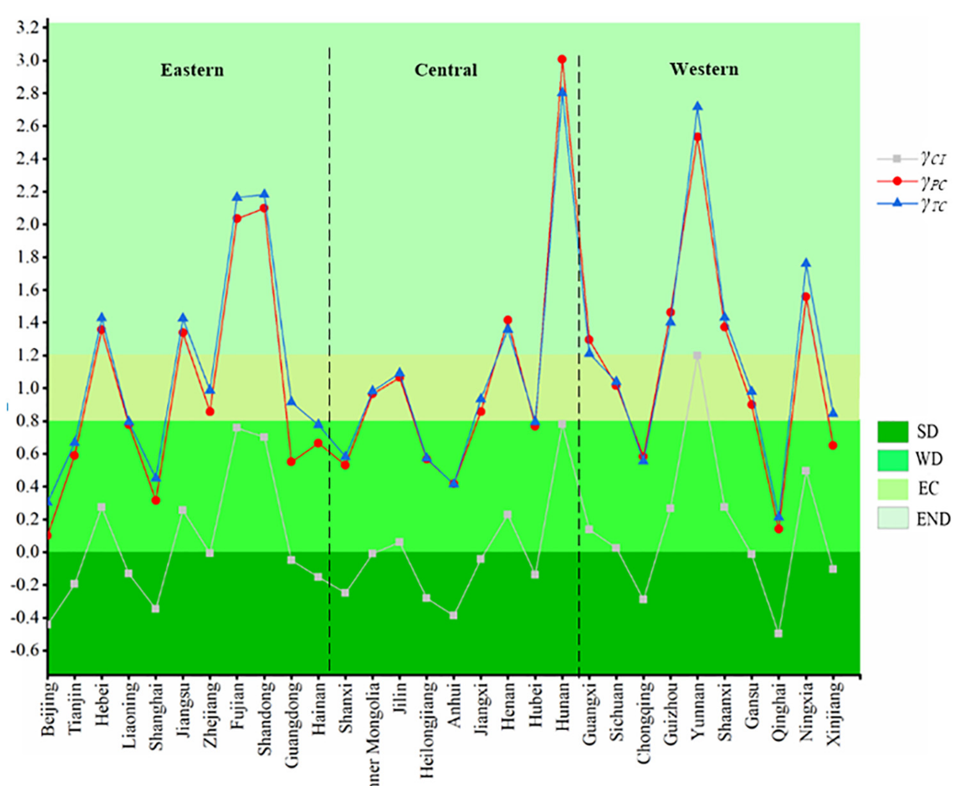


Fig. 6. Decoupling results during the 10th *FYP* period (2001–2005).

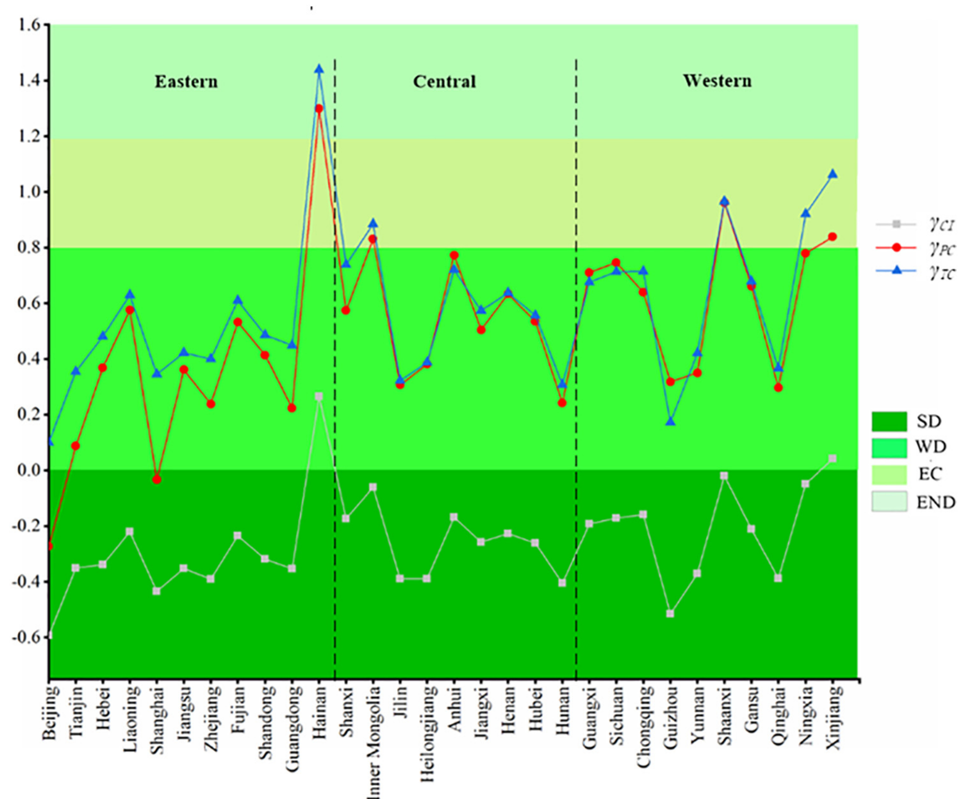


Fig. 7. Decoupling results during the 11th *FYP* period (2006–2010).

(1) Decoupling elasticities of γ_{CI} in all these 30 provinces were significantly smaller than that of γ_{PC} and γ_{TC} across all the three surveyed periods, indicating that it is easier to decouple from *CI* at provincial level. As *CI* is the ratio of *TC* to *GDP*, *CI* will decrease with the boosted *GDP* (Shen et al., 2018b). On the other hand, the decrease of *CI* also reflects the improvement of production

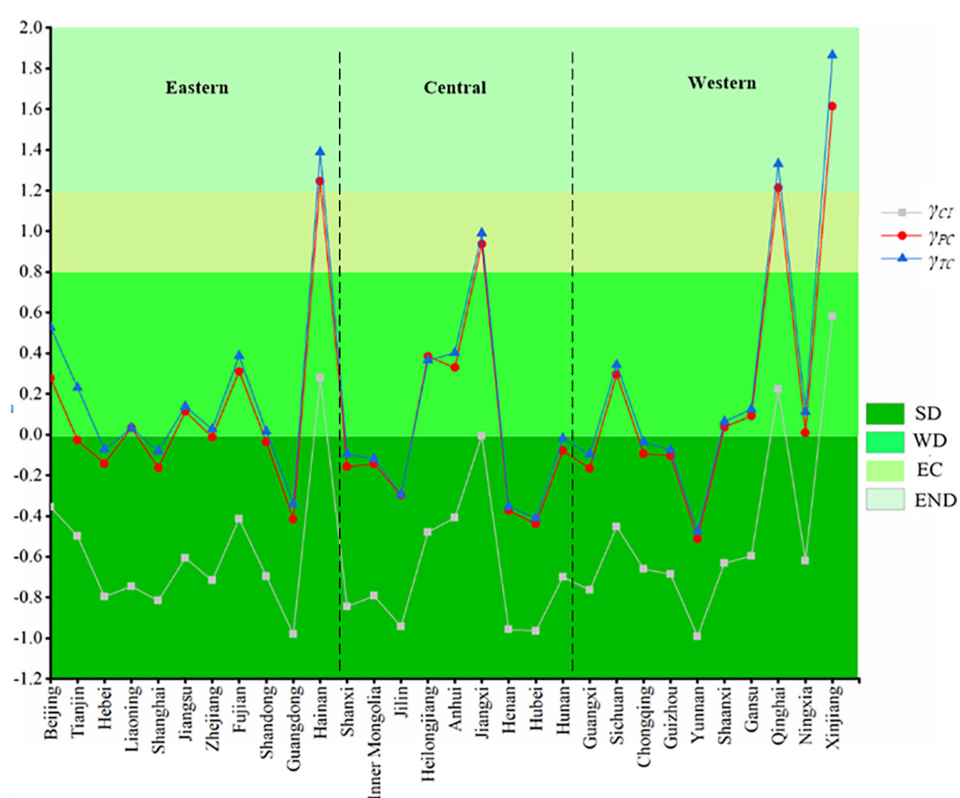


Fig. 8. Decoupling results during the 12th *FYP* period (2011–2015)

efficiency, which is the precondition of reducing *PC* and *TC* (Roberts and Grimes, 1997). Thus, it is considered important for regions to set appropriate baselines for achieving the *SD* state in referring to *CI*, which provides a basis for achieving the state of *SD* in referring to *PC* and *TC*.

(2) It is interesting to note that the decoupling elasticities γ_{PC} and γ_{TC} were relatively close and they may even overlap sometimes, as demonstrated in Figs. 6–8, which is also concluded by Chen et al. (2010). This can be proved by the fact that carbon indicator *PC* just discriminates part of the influence of population in comparing to *TC*, as *PC* is the ratio of *TC* to population (Pao and Tsai, 2011). With the relatively steady increase or even decline of the total population in the Chinese provinces, the subtle differences of the γ_{PC} and γ_{TC} are reasonable. Under this circumstance, in regions where total population present rapid growth, their decoupling states for carbon emission exhibit a three-step pattern, i.e. decoupling *GDP* from *CI*, *PC*, and *TC* successively. In this regard, governments can formulate correspondingly a three-step strategy for low carbon economy (Shuai et al., 2019).

(3) Different from the expectation that *SD* state would easily occur in economically advanced provinces, the decoupling states of *CI*, *PC* and *TC* in the economically developed Eastern provinces were not significantly superior to those economically undeveloped Central and Western provinces, as shown in Figs. 6-8. Therefore, this result disagrees with the finding by Shuai et al. (2019), who suggested that improving income level can spur the absolute decoupling. Wu et al. (2019) pointed out that this was because the traditional perception of economic advancement in Eastern, Central and Western successively is partially correct. Wang and Zhao (2014) further argued that the regional division of Eastern, Central and Western was not proper for analyzing the provincial carbon emissions in China. It can be explained by the fact that, both Hainan and Shandong are located in Eastern China, but the value of *TC* in Shandong is over 22 times as that of Hainan (Zhou and Liu, 2016).

3.2. Decomposition results of carbon emission changes

Given the fact that reducing *TC* is the key for completely decoupling *GDP* from carbon emissions, this section examines the effects of *ES*, *EI*, *EO*, and *P* to *TC* in the 30 provinces by employing the decomposition models (3)–(9). The detail results are shown in Figs. 9–11.

3.2.1. Energy structure (ES)

Figs. 9–11 show that the effect of *ES* on the increase of *TC* can be positive or negative during the 10th, 11th and 12th *FYP* periods. Xu et al. (2016b) also obtained similar conclusion, explaining that this was due to the changing proportion of coal consumption. For example, Figure 9 reveals that *ES* effect in Shanxi province played the most important role in inhibiting *TC* during 2001–2005. This matched well with the fact that Shanxi is a major coal producer with high concentration of heavy industry, and has formulated a series of policies to control its coal consumption, such as eliminating small coal mines with outdated productivity, monitoring energy-intensive industries. As a result, Shanxi's proportion of coal in total energy consumption has declined from 32.1% in 2001 to 28.3% in 2005 (National Bureau of Statistics of China (NBSC), 2015a). On the contrary, *ES* contributed most significantly to the increase of *TC* in Ningxia province, as shown in Fig. 9. Since the economic development level of Ningxia was low in China, it has expanded greatly resource-related heavy manufacturing to propel the economy in recent years (Bai et al., 2016). This leads to the proportion of secondary industry to *GDP* increased by 5.6% during the 10th *FYP* period, which in turn inevitably exacerbated the coal consumption and thus emit more carbon emissions. These explanations are also applicable to the *ES* effect on *TC* in Figs. 10 and 11.

In view of the results in Fig. 9–11, it can be concluded that *ES* is an insignificant contributor to affecting *TC* for most provinces, and its effect had little changing tendency in the three periods. This is mainly because China's energy is characterized by "more coal, less oil, gas shortage", making it is very difficult to change the coal-oriented structure (Xu et al., 2016a). Obviously, this is not a good message under the background of accelerated urbanization and industrialization in China, which is subject to the excessive demand for energy, especially of coal, and thus lead to huge generation of *TC* (Zhang and Lin, 2012). In this regard, the central government must make strict laws or regulations for deep processing of raw coal, accelerating the elimination of outdated coal production facilities, and strengthening supervision coal-intensive industries (Chen et al., 2016). Furthermore, the Chinese government should actively encourage regions to gradually change the extensive type of coal consumption with consideration of the local resource advantages. For example, those economically developed regions like Beijing and Shanghai can increase the technological investment on cleaner energy, while rich-resource bases such as Guizhou can make full use of its rich water resources.

3.2.2. Energy intensity (EI)

Figs. 9–11 reveal that *EI* has fluctuating effect on the increase of *TC*, changing between positive and negative. This is in line with the findings by Xu et al. (2016b), Li et al. (2017) and Zhou et al. (2016). As mentioned in Section 2.2, the reduction of *EI* indicates the improvement of energy efficiency. However, the impact of energy efficiency on *TC* is two-sides. On one hand, it is widely appreciated that the improved energy efficiency can make full use of energy, and thus play an important role in curbing *TC* (Shuai et al., 2018; Shuai et al., 2017b). On the other

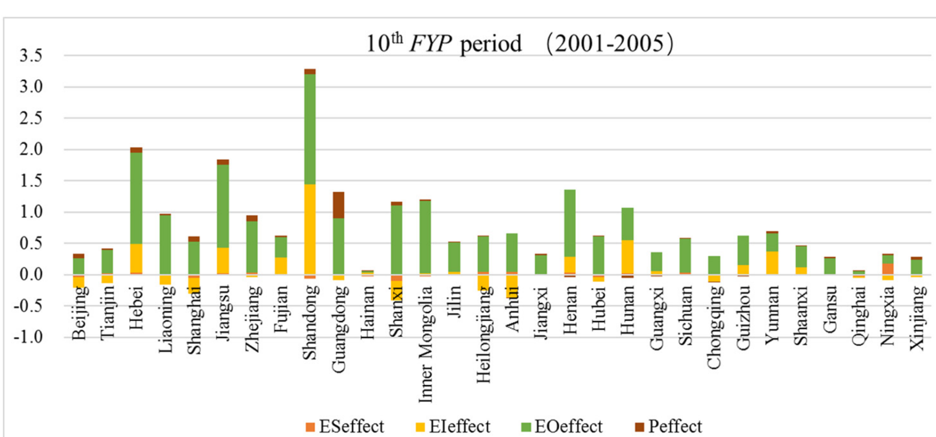


Fig. 9. Effects of emissions factors (*ES*, *EI*, *EO*, *P*) in the 30 provinces during 2001–2005

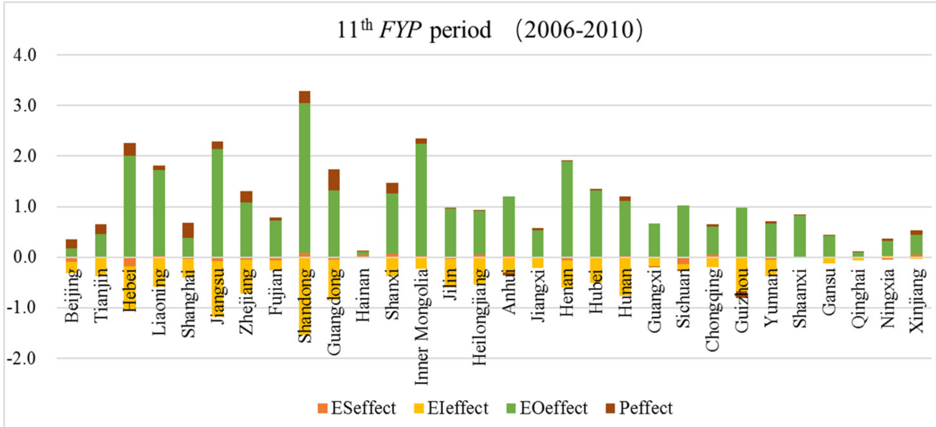


Fig. 10. Effects of emissions factors (*ES*, *EI*, *EO*, *P*) in the 30 provinces during 2006–2010.

hand, because of the rebound effect, the energy saved from the energy efficiency was offset by the new energy demand generated by the scale effect. For example, the improvement in energy efficiency leads to fall in price, so cars sale expanded greatly, resulting in the increase of *TC* (Wang and Zhao, 2014). Consequently, the negative effect of *EI* on reducing *TC* is not only because of the degradation in energy efficiency but also the scale effect, while the positive effect of *EI* on reducing *TC* indicates the great strides of energy utilization technologies. Notably, despite of the two-side effects, Figs. 9–11 show that reducing *EI* is still considered as the most effective way to restrict *TC*, as proposed by Dong et al. (2019) and Zhou et al. (2016). This indicates that policy strategies aiming to improve energy efficiency should be further formulated. Specific measures should be taken, such as strengthening the supervision and management of energy conservation, encouraging high-tech industries vigorously, increasing the technical investment and reducing the tax for low-carbon enterprises.

Furthermore, it can be seen from the Figs. 9–11 that the effect of *EI* was mixed and weaker during the 10th *FYP* period, but increased continuously and became increasingly significant in the 11th and 12th *FYP* periods. As shown in Fig. 9, there were only 14 provinces with inhibitory effect of *EI* on *TC* reduction. Among these provinces, *EI* in Shanxi province had the greatest inhibitory effect which contributed to *TC* decrease. However, *EI* in all the 30 provinces presented a positive impact on *TC* reduction during the 12th *FYP* period with greater inhibitory effect than that of Shanxi province in the period of 2001–2005, except in Hainan Jiangxi, Qinghai and Xinjiang. Consequently, the role of *EI* was very effective in reducing *TC* in the 11th and 12th *FYP* periods. This result is not surprising, because the target of "reducing energy intensity by 20% from 2005–2010 and by 16% from 2011–2015" was officially proposed in the 11th and 12th *FYPs* respectively. Furthermore, it is interesting to find that the effects of *EI* on reducing *TC* in the majority of Eastern and Central provinces were much more significant in comparing to the Western provinces. This is similar to the conclusion by Shuai et al. (2017b) and Wang and Zhao (2014), who suggested that higher economic development level contributed to greater impact of *EI* on curbing *TC*. The main reason for this result is that provinces with advanced economy can afford to increase the R&D investment, resulting in better energy-saving and abatement technologies (Xu and Lin, 2016). For example, the average annual R&D investment in Shandong is 115.44 billion Yuan during the 12th *FYP* period, which is more than 10 times of that in Qinghai. Thus, regions with high economic development level should pay additional attention to promoting low-carbon technologies. And it is necessary for the national government to break up the technology inequity, and actively encourage the sharing and transferring of low-carbon technologies between provinces.

3.2.3. Economic output (EO)

In terms of per capita GDP (*EO*), it appeared as the dominant contributor to the increase of *TC* in the 30 provinces during the three periods (Figs. 9–11). This result is in line with the findings of an array of previous literature (Xu et al., 2016b; Zhou et al., 2016). The effect of *EO* was obviously greater on increasing *TC* in Shandong and Henan during the 12th *FYP* period, as shown in Fig. 11. According to the China Statistical Yearbook, the annual average growth rate of per capita *GDP* in these two provinces was 9.02% and 9.07% respectively during 2011–2015. This increment of per capita *GDP* reflects not only economic growth

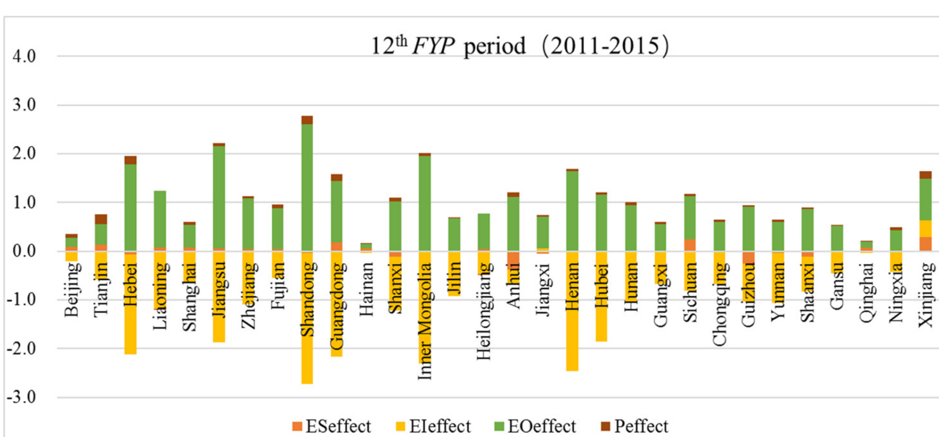


Fig. 11. Effects of emissions factors (*ES*, *EI*, *EO*, *P*) in the 30 provinces during 2011–2015

but also the improvement of life quality (Xu et al., 2014a). On one hand, as the most basic element for production, energy drives economic development but also emits carbon emissions (Zhou and Liu, 2016). On the other hand, the improvement of life quality leads to a substantial increase in demand for energy products, which are accompanied by the increase of energy consumption and carbon emissions. For example, the average household car per 100 households in Shandong province increased from 28.12 in 2011 to 37.8 in 2015, while that in Henan province increased from 14.06 to 17.4 during 2011–2015.

Figs. 9–11 also show that *EO* effect on carbon emissions in most provinces was in the order of 11th *FYP* period > 10th *FYP* period > 12th *FYP* period. This can be proved by the fact that the average growth rate of *EO* during these three periods was 12.83%, 12.3% and 8%, respectively. In fact, the focus of economic development was closely inseparable from the periodic development strategy in China. As mentioned above, during the 10th *FYP* period, China joined the WTO and gradually enlarged the scale of industrial transfer to propel economic development. During the period of 11th *FYP*, the Chinese government established its long-term policy guidelines to expand domestic demand and implemented expansionary fiscal and monetary policies, resulting in rapid economic growth (Xu et al., 2016a). However, during the 12th *FYP* period, China emphasized on the quality of economy and had made great efforts to regulate the overheated economy and avoid unnecessary construction, which led to the economic growth rate shrunk dramatically (Yang et al., 2018). Therefore, it is important to develop economy with considering both speed and quality. This is similar to the findings of Xu et al. (2014b), who suggested that fast and steady economic growth can significantly help control the increase of *TC*. In this regard, some efforts should be made, such as low-carbon economy pilot demonstration, emission trading emissions permit, green construction chain and industrial structure adjustment towards tertiary industry (Shen et al., 2016; Song et al., 2018; Tam and Lu, 2016; Wang and Tam, 2016).

3.2.4. Population size (P)

In referring to the emission factor *P*, Figs. 9–11 show that the effect of *P* on increasing *TC* was positive but insignificant in most provinces. This result was supported by Zhu et al. (2013) and Xu et al. (2014a) who proposed that the provinces in China are populous and their population scales have shown an increasing trend for a long time. Population drove considerably growth in cement and energy demand for large-scale construction and transport infrastructure, inevitably leading to greater *TC*. Fan et al. (2013) pointed out that since 1996, the proportional energy consumption for residential use has increased by 19% and 9% in rural and urban areas respectively in China. However, family planning as a fundamental State policy was developed and had been successful to control the rapid population growth in China. During the 2006–2010, the annual growth rate of China's total population was only 0.499% and the total scale reached to 1.34 billion in 2010, which was 20 million less than the population cap established in the 11th *FYP*. Although this slow increase in population can restrict *TC*, Wu et al. (2016) and Zhang and Tan (2016) argued that it also caused emerging problems such as imbalance of population structure and ageing population, which were significantly correlated to increase social security burdens. With addition of the contradictions between high production demand and the low population growth, the two-child policy has gradually been relaxed in China. Obviously, this will necessarily propel the population growth in the long term, with a concomitant influence on increasing *TC* (Wu et al., 2016). Therefore, it is important for China to learn the valuable experience from the developed regions in the coordination of population growth and economic development, resource depletion and carbon emission controlling (Zhou and Liu, 2016). For example, an emission-reduction education system should be vigorously promoted in the community and schools to improve people's consciousness on low-carbon lifestyle.

By comparing the results in Figs. 9, 10 and 11, it is interesting to observe that the impact of *P* on *TC* declined continuously from Eastern provinces to Central and Western province. This result agrees with the assessment by Zhou and Liu (2016), but different from the findings by Wang and Zhao (2014), who suggested that *P* has a greater effect on increasing *TC* in developing region than that in underdeveloped and highly developed regions. The possible reason behind this difference is that rural-urban migration, particularly with regard to the urban working-age population, has been ignored. In fact, China has witnessed the world's greatest rural-migration, and the Eastern provinces were the primary destinations, due to the better location, education, healthcare, and convenient transportation (Chan, 2012; Peng et al., 2015). For example, the population of Guangdong increased by 10.58% from 2006 to 2010, contributing to increase *TC* by 0.413×10^8 t, while the population of Guizhou decreased by 5.7%, contributing to the decrease of *TC* by 0.137×10^8 t, as shown in Fig. 10. Furthermore, the agglomerative urban population in the Eastern provinces is dominantly characterized by working-age population (population aged 15–64), which further contributed to higher level of industrialization, with a concomitant influence on energy demand and *TC* increase (Zhou and Liu, 2016). Therefore, policies that respond to balance the age structure between regions should be seriously considered (Zhu and Peng, 2012). It is necessary to improve the existing household registration system for attracting migrant workers to different urban areas apart from Eastern provinces (Fan and Lei, 2017).

4. Conclusion

This paper examines the decoupling relationship in the 30 Chinese provinces from three perspectives, namely, the relation between *GDP* and carbon intensity (*CI*), *GDP* and per capita carbon emissions (*PC*), and *GDP* and total carbon emissions (*TC*). The impacts of emission factors of energy structure (*ES*), energy intensity (*EI*), economic output (*EO*), and population size (*P*) on *TC* are analyzed by using LMDI model. The following conclusions can be made:

(1) During the period from 2001–2015, the dominate decoupling state of *CI* in the 30 provinces has gradually shifted from weak decoupling to strong decoupling, while the growth rates of *PC* and *TC* were gradually lower than that of economic growth. In other words, the decoupling degrees of *CI*, *PC* and *TC* have made great strides in accordance with the development strategy of China's economic belts during the whole surveyed period of 10th, 11th, and 12th *FYP*.
(2) There existed a strong decoupling relationship between GDP and *CI* in most provinces except Hainan, Qinghai and Xinjiang during the 12th *FYP* period, indicating that economic growth has been disassociated with *CI*. However, there is a big room for the Chinese economic growth to decouple from *PC* and *TC*.
(3) In general, *EO* and *EI* are the dominated inhibiting and promoting factors for carbon emission reduction, respectively. Thus, the Chinese government should pay attention to balance the speed and quality of economy, and improve technology to raise the energy efficiency as well. The effect of *ES* on the increase of carbon emissions changes between positive and negative, where Anhui, Shanxi, and Hebei play the most significant role in curbing carbon emissions. *P* is an insignificant contributor to increasing carbon emissions, which has greater impact in economically developed provinces.
(4) Owing to the continuous and stricter policies on energy conservation and carbon emissions in the period of 12th *FYP*, the inhibiting effect of *EI* on the reduction of carbon emissions was gradually reinforced, particularly for economically advanced provinces such as Shandong, Guangdong, Hebei, and Inner Mongolia. Simultaneously, the promoting effect of *EO* on the increase of carbon emissions tended to be weaker for most

provinces. To coordinate regional economic development and carbon emission, different measures should be adopted rather than a "one-size-fit-all" approach.

Some limitations exist in this research. First, this study only provides an initial interpretation of the impact of energy structure, energy intensity, economic output, and population on carbon emission for each province in China. Other emission factors such as urbanization and population structure can be considered in further study. Second, fixed coefficients of carbon emissions for different types of energy resources are used due to data unavailability. The research methods in this study can be adopted to investigate comparatively study for regions in different countries.

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